NIST Reference Spectroradiometer for Color Display Calibrations

Steven W. Brown and Yoshi Ohno
Optical Technology Division
National Institute of Standards and Technology
Gaithersburg, Maryland, USA

Abstract

A program to develop calibration services for color-measuring instruments has been established recently at the National Institute of Standards and Technology (NIST) to address commercial and industrial needs for higher-accuracy measurements of displays. In particular, a reference spectroradiometer has been built with the goal of enabling measurements of displays with the smallest possible uncertainty. The instrument has been characterized for wavelength error, variable bandpass, stray light, linearity and random noise. The accuracy of color measurements with this instrument has been assessed using detailed simulations incorporating the measured performance characteristics of the instrument. In the simulations, the uncertainty in color measurements of sixteen CRT and LCD display colors was calculated. The results of the simulations imply that the instrument is capable of measuring colors of displays with a combined standard uncertainty of approximately 0.001 in chromaticity (x,y) and 1 % in luminance (Y).

Introduction

Color management of displays — including CRTs and flat panel displays — is becoming increasingly important as the quality of displays continues to improve and customers demand higher accuracy in color reproduction. Accurate color management is, of course, based on the accurate measurement of colors. Colorimeters and spectroradiometers are commonly used to measure the chromaticity of displays, and useful protocols for color measurement using these instruments have been developed [1,2]. The instruments are normally calibrated against an incandescent standard lamp, and errors for display colors (having very different spectra) tend to be much larger than manufacturers' specifications (normally stated for CIE Illuminant A). For example, inter-instrument variations for chromaticity measurements as large as 0.01 in x, y have been observed for both high-quality tristimulus colorimeters and diode-array spectroradiometers when measuring various colors of a display. Such measurement uncertainties significantly degrade the performance of any color management system.

To address the need for higher-accuracy measurements of displays, a program has been established at NIST to develop standards and calibration services for color-measuring instruments. By utilizing a recently developed matrix correction method [3,4], the chromaticity uncertainties can be reduced to less than 0.001 in x,y with respect to a reference instrument. A reference spectroradiometer has therefore been designed and built with the goal of enabling measurements of displays with the smallest possible uncertainty. The spectroradiometer has been characterized for wavelength error, variable bandpass, stray light, linearity and random noise.

To assess the accuracy of display color measurements with the instrument, a series of computer simulations has been conducted relating each uncertainty component of the spectroradiometer to the magnitude of measurement uncertainty in both chromaticity and luminance. The simulations were conducted using spectral data from both a CRT and an LCD display. Based on the results of the simulations, the NIST reference spectroradiometer should be able to measure colors with an approximate combined standard uncertainty of 0.001 in x,y and 1 % in Y.

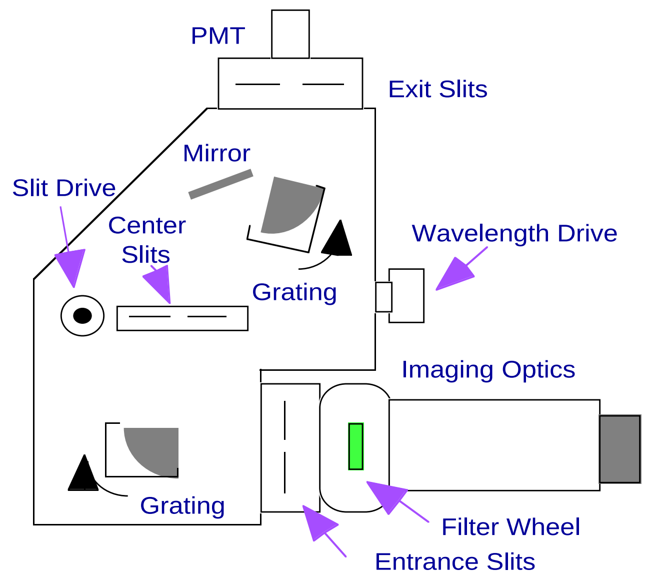

Figure 1. Schematic diagram of the reference spectroradiometer.

Reference Spectroradiometer

The developed spectroradiometer, shown in Fig. 1, employs a double grating scanning monochromator equipped with imaging optics to allow measurement of spectral radiance. An opal glass diffuser placed in front of the monochromator entrance slits minimizes polarization effects. Order-sorting filters eliminate higher-order grating diffraction effects. The center slits are equipped with a stepper motor, enabling remote control of the slit width and consequently the bandpass of the instrument as well. The signal is detected with a photomultiplier tube and measured with a digital voltmeter. The entire measurement system, including an optical table, is installed in a light-tight box to minimize ambient stray-light errors. The spectroradiometer is calibrated against NIST spectral irradiance standard lamps [5] used with a calibrated pressed-PTFE plaque [6].

The spectroradiometer was characterized for wavelength errors, bandpass variations, stray light, random noise, and linearity. The uncorrected wavelength error and the wavelength-dependent bandpass of the radiometer are shown in Fig. 2. Fitting the measured error to a third order polynomial function and using the resulting polynomial to correct the wavelength drive of the monochrometer reduced the wavelength uncertainty to less than 0.1 nm. The bandpass variations are reduced by varying the center slit width. Using wavelength-calibration "pen" lamps and lasers, the center slit width was adjusted to give a triangular bandshape with a 5 nm bandpass at 10 different wavelengths over the visible spectral range. The data were subsequently fit to a third order polynomial to determine the appropriate slit width at intermediate wavelengths. The corrected bandpass is accurate to within approximately 0.1 nm.

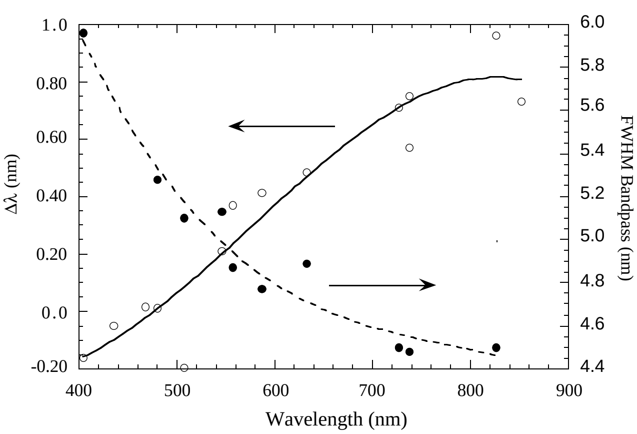

Figure 2. The uncorrected wavelength error (open circles) and the wavelength-dependent bandpass (closed circles) of the spectroradiometer. The solid and dashed lines are third-order polynomial fits to the data.

The linearity of the response of the instrument was measured using the NIST Beam Conjoiner [7]. The instrument response deviated from linearity by less than 0.1 % over 4 orders of magnitude in the flux range where display measurements are typically made. The random noise was estimated to be on the order of 0.1 % of the peak signal by making repeated measurements of a CRT and an LCD display.

Computer Simulations

A computer program was developed to simulate contributions of wavelength errors, wavelength repeatability, bandpass variation, stray light, and random noise to the total chromaticity measurement uncertainty. The simulation first incorporates the various uncertainty components into the instrument calibration, and then calculates and outputs the detector signal (with errors) at each wavelength for a given spectrum. The spectral data are internally processed at 0.1 nm intervals. The chromaticity coordinates x, y and the luminance Y are finally calculated and compared with the true values. The simulations have been used to estimate the uncertainty in color measurements of reference standard tiles as well as displays, and to estimate the uncertainty in color measurements using instruments with differing operating characteristics.

In this work, simulations were conducted for 16 different colors of a CRT and an LCD display including primary colors and white. The primary red, green and blue spectra from the two displays are shown in Fig. 3. The additional 12 colors used in the simulations for each display were obtained by mixing the primary colors using different combinations of the ratios 255, 100, and 50. The measured values of the uncertainties in color measurement associated with the spectroradiometer were incorporated directly into the simulation program to estimate the accuracy of color measurements using the instrument. When random noise was included, the simulation was repeated a minimum of 300 times for each color to allow for statistical analysis.

Results

The simulations included 0.1 % random noise, a stray light factor of 10^{-6}, a random wavelength error of 0.1 nm, and a random bandpass variation of 0.1 nm. Without correcting for instrumental wavelength and bandpass errors (using data shown in Fig. 2), the mean error in chromaticity measurements (defined as the mean difference between the calculated and the true values) of displays can be as large as .0012 in x and 0.0009 in y for the green LCD color. Correcting for wavelength and bandpass errors, the mean chromaticity error can be reduced to less than 0.0001 for both x and y.

However, the combined standard uncertainty of the measurements can be significantly larger. The results are summarized in Tables 1 and 2 for the CRT and the LCD display, respectively. Only the data for the primary colors and white are shown; the standard deviations in chromaticity coordinates for measurements of the other colors were less than those obtained for the three primary colors. The results show that the combined standard uncertainty in chromaticity measurements of the CRT can be as large as 0.0006 in x and 0.0004 in y when measuring the red primary color. For the LCD display, the combined standard uncertainty can be as large as 0.0007 in x and 0.0013 in y when measuring the green color.

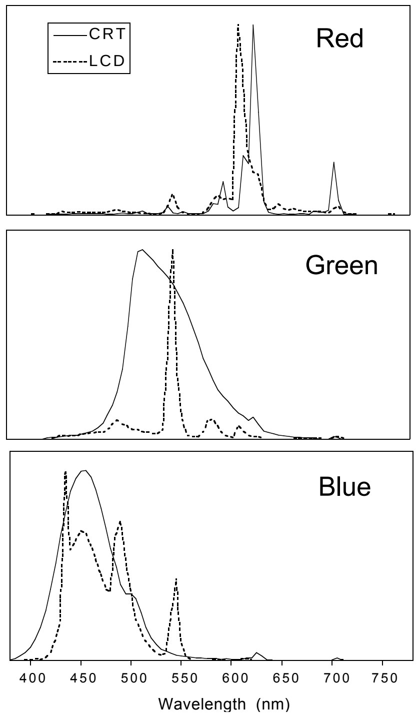

Figure. 3. Primary red (top), green (middle), and blue (bottom) spectra from a CRT and an LCD display used in the simulations of color measurement.

Table 1. Results of computer simulations of the uncertainty of color measurements of a CRT display. The standard deviations of x, y and Y are listed for each color.

CRT Colors	Δx	Δy	ΔY (%)
White	0.0003	0.0001	0.1
Red	0.0006	0.0004	0.4
Green	0.0002	0.0002	0.1
Blue	0.0001	0.0002	0.3

Table 2. Results of computer simulations of the uncertainty of color measurements of an LCD display. The standard deviations of x, y and Y are listed for each color.

LCD Colors	Δx	Δy	ΔY (%)
White	0.0008	0.0012	0.7
Red	0.0008	0.0005	0.8
Green	0.0007	0.0013	0.7
Blue	0.0002	0.0005	0.4

The simulations demonstrate that the reference spectroradiometer, corrected for wavelength error and variable bandpass, is capable of measuring CRTs and LCDs with an approximate combined standard uncertainty of 0.001 in x, y and 1 % in Y. After correcting the wavelength errors and variable bandpass of the spectroradiometer, the major uncertainty component is the random noise associated with the measurement. The simulations will be extended to different types of displays and compared with display measurements to ensure the predicted accuracy of color measurements with the instrument.

Conclusions

A reference spectroradiometer has been developed at NIST for color measurements of displays. Detailed simulations of the performance of the instrument, based on careful measurements of the operating characteristics, show that it should be capable of achieving a combined standard uncertainty of approximately 0.001 in x, y and 1 % in Y for various colors of a typical color display. A calibration service is under development at NIST for color measuring instruments that can be used to certify their absolute accuracy. Colorimeters and spectroradiometers will be calibrated against the NIST reference spectroradiometer for several different colors of a particular display.

Acknowledgements

We would like to acknowledge contributions to this work by Y. Zong and H. Yoon. This work is supported by the U.S. Air Force under CCG contract 97-422.

References

1. ASTM E1455-92, “Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters.”
2. ASTM E1336-91, “Standard Test Method for Obtaining Colorimetric Data From a Visual Display Unit by Spectroradiometry.”
3. Y. Ohno and J. Hardis, “Four-Color Matrix Method for Correction of Tristimulus Colorimeters,” Proc. Fifth IS&T Color Imaging Conference, 301 (1997).
4. Y. Ohno and S. Brown, “Four-Color Matrix Method for Correction of Tristimulus Colorimeters: Part 2,” to be published in the Proc. Sixth IS&T Color Imaging Conference (1998).
5. J. H. Walker, R. D. Saunders, J. K. Jackson, and D. A. McSparron, “Spectral Irradiance Calibrations,” NBS SP 250-20, U. S. Government Printing Office, Washington, DC, 1987.
6. P. Y. Barnes, E. A. Early, and A. C. Parr, “Spectral Reflectance,” NIST SP 250-48, U.S. Government Printing Office, Washington, DC, 1998.
7. Ambler Thompson and How-More Chen, “Beamcon III, a Linearity Measurement Instrument for Optical Detectors,” *J. Res. Natl. Inst. Stand. Technol.* **99**, 751(1994).